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AUDITORY PATTERN MEMORY

Mechanisms of Tonal Sequence Discrimination by Human Observers

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A two-process model of pattern discrimination was developed to describe how tonal sequences are processed, stored, and discriminated by human observers. The model was evaluated in tasks in which observers were required to discriminate between the spectral or temporal patterns encoded in two sequences of tones. The experimental results supported the assumptions of a trace/context coding theory. The trace mechanism is relatively insensitive to temporal transformations made to frequency-coded patterns but relatively sensitive to temporal transformations made to temporally coded patterns. The effects of intervening maskers on the trace were also evaluated. Keywords;

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SUMMARY

A two-process model of pattern discrimination was developed to describe how tonal sequences are processed, stored, and discriminated by the human auditory system. In this model, the comparison of auditory stimuli involves processsing in two separate concurrent modes, with the mode contributing the least variance having the dominant effect on performance. In the 'sensory trace' mode, the subject compares a trace of the auditory sensation to the corresponding trace of a subsequent stimulus. The trace is assumed to decay with time, but be independent of the number and range of possible stimuli. In the 'context coding' mode, stimuli are discriminated by comparing encoded representations, each representation consisting of a comparison between the given stimulus and the overall context of other stimuli heard. The quality of the encoded representation is assumed to depend on the size of the auditory context.

This model was applied to tasks in which a subject compared two sequences of tones and judged whether the frequency patterns were the same or different. Several aspects of the sequences were varied: (a) the temporal variability of the sequences, (b) the correlaton between the temporal envelopes of each pair of sequences presented on a trial, and (3) the time interval between the two sequences. In the 'correlated' condition, the two sequences on a trial had identical temporal patterns, while in the 'uncorrelated' condition, all sequence temporal patterns were generated independently. In order to study the properties of the trace mechanism, various temporal and spectral transformations were made to the second sequence of each pair. In addition, maskers consisting of short tonal sequences were interposed between the first and second sequence on each trial.

Performance in the correlated conditions was independent of temporal variability, but decreased with increases in the time interval between the sequences. Performance in the uncorrelated condition decreased with increased temporal variability, and was independent of the length of the intersequence interval. These results support the assumptions of the trace/context theory; good fits were obtained between data from human observers and the predictions of the two-process model. Performance in the correlated condition was insensitive to temporal transformations made to the second sequence, suggesting either (a) that traces can be temporally scaled for comparison with other stimuli, or (b) that sensory traces can be generated for separate aspects of a stimulus. Performance under different frequency transformations produced a pattern of results consistent with (b). The effects of interfering events occurring during the time interval between the sequences were not consistent with conventional assumptions about interruption or masking of the trace mechanism.

A series of experiments on temporal pattern discrimination was begun in which the observer had to discriminate between two tonal sequences having the same or different temporal patterns.

These tasks were evaluated under different levels of pattern difference and average duration, and under different amounts of temporal compression and expansion. Performance was found to be very sensitive to the temporal transformation imposed on the stimuli. Models of temporal pattern discrimination are currently being evaluated in a revised task paradigm.

Some general assumptions of the signal detection model were evaluated in experiments on the detection and recognition of multiple element auditory and visual displays. A major interest in these experiments was to describe how the observer aggregates information over the elements of the sequentially or simultaneously presented elements of the display. The results were consistent with expectations: (a) in sequential auditory displays, first and last arriving elements are emphasized, (b) with visual displays, elements in the fixated region are emphasized (the effective size of the region depends on the element coding and format), (c) with both auditory and visual displays, high information-carrying elements are emphasized, and (d) with the visual displays thus far evaluated, the basic relationships predicted by the recognition-detection model are supported.

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1. INTRODUCTION AND PURPOSE

The goal of this research is to understand how human listeners process and store brief sequences of sounds. Specifying how humans encode and remember such stimulus patterns is an important goal for a theory of auditory information processing, and is a necessary requirement for understanding complex perceptual processes such as speech. We have developed a general paradigm for studying the memory processes involved in the perception of auditory patterns, using tasks in which the temporal and spectral properties of tonal sequences are systematically manipulated.

1.1 Basic Experimental Paradigm

When a subject must judge the similarity of the frequency patterns defined by two sequences of tones, variation in the timing of the tones can have a deleterious effect on performance. This effect is most evident when the tonal sequences have unique temporal patterns. Under such conditions, it may be difficult for the subject to tell whether or not the frequency patterns are the same or different. Our experiments have demonstrated that variability in the temporal aspects of a tonal sequence has a large effect on a subject's ability to make discriminations based on the <u>frequency</u> pattern of the sequence. We have employed this sequence discrimination task to evaluate a model of human pattern discrimination, and have studied some properties of the memory process and candidate mechanisms of the sequence comparison process.

Many investigators have noted that varying the parameters of a tonal sequence can have a large effect on performance in a discrimination or detection task. For example, Watson and his colleagues have reported a number of studies in which a subject must detect small differences between two tonal sequences whose parameters vary across the sequence of experimental trials. This type of trial-by-trial variation can have an effect on the detectability of a small change in the frequency, duration, or intensity of one component of the tonal sequence (Watson, Kelly & Wroton, 1976; Watson & Kelly, 1981; Spiegel, & Watson, 1981; and Leek & Watson, 1984). Watson (1987) has pointed out that these effects can be much larger than those obtained from single tone (2IFC) discrimination tasks in which the tone parameters vary over trials.

We reported similar effects in an experiment testing the discrimination of temporal jitter in tonal sequences (Sorkin, Boggs & Brady, 1982), and in more recent frequency pattern discrimination experiments in which the temporal pattern was varied (Sorkin, 1987b). The subject's task in the recent experiments was a Same/Different task: subjects were presented with a pair of tonal sequences and had to determine if the two sequences had the same or different frequency patterns. Subjects were to ignore variations in the temporal structure of the sequences, such as jitter in the tone onsets, durations, or inter-tone gaps.

Figure 1 illustrates some of the tonal sequences possible on trials in our sequence experiments. In condition, C, the correlated temporal condition, the pattern of tone onsets, durations, and inter-tone gaps was identical in the two sequences of each trial. For this particular pair of sequences the frequency pattern is different in the two sequences, so that the correct response is "different" on this trial. The second pair of sequences illustrates condition U, the uncorrelated condition. Here the tone onsets, durations, and gaps were uncorrelated between the two sequences. The frequency pattern is identical on the trial shown, hence the correct response is "same". The temporal variability of the sequences was the major experimental variable in this paradigm: in the correlated condition, the temporal variation was only present across trials; in the uncorrelated condition, the variation was present both within and across trials.

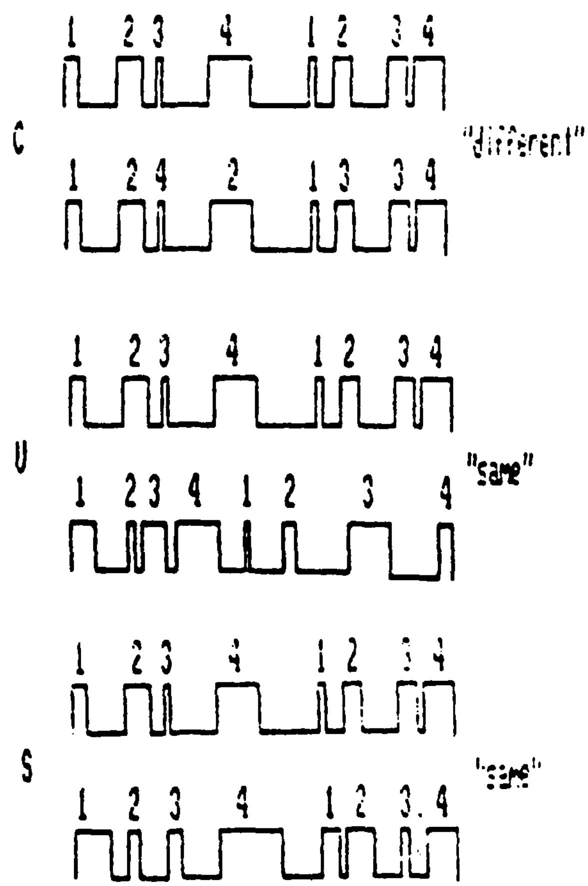

Figure 1. Examples of pairs of sequences present on trials of the experimental task.

There are other ways that the temporal properties of the sequences could be varied. For example, the last pair of sequences illustrates the synchronized (S) condition. In this condition the tone onsets were identical in the two sequences, but the durations and gaps varied. In this particular pair of sequences the frequency pattern is identical, so the correct response is "same". In another condition (figure 5) all durations and gaps in the first sequence of each pair were scaled upward by a constant factor, so that the new sequence was an expanded version of the first. In all tasks, the subjects were told to base their response only on the <u>tonal pattern</u> of each sequence.

2. TWO-PROCESS PATTERN DISCRIMINATION THEORY

In a standard type of signal detection task, detectability, d′, is proportional to signal power, I, and to the square root of the signal duration, t. It is inversely proportional to the square root of the sum of two variances: The external noise power density, σ_n^2, and any internal noise or sensory variance σ_s^2. Equation 1 illustrates this relationship.

$$d' = kI\ t/\left[\sigma_n^2 + \sigma_s^2\right]^{-1/2} \qquad (1)$$

The detectability is also a function of various memory parameters that are specific to the particular task. For example, a single-interval yes-no detection task clearly has different memory requirements than does a two-interval intensity discrimination task.

Tanner (1961) proposed a general framework for categorizing the memory requirements of a variety of single and two-interval psychophysical tasks; this scheme has been extended and quantified by a number of workers including Sorkin (1962), and Macmillan, Kaplan, and Creelman (1977) in a study of categorical perception. Tanner's model included a short-term decaying memory for the acoustic input to the system plus various interference factors and long-term memory factors. The trace decay component of the Tanner model was extended in a paper by Kinchla & Smyzer (1967) and later incorporated as the trace component of the trace-context model of Durlach and Braida (1969) and their colleagues (Berliner and Durlach, 1973). In Sorkin (1984), we proposed that the Durlach and Braida dual mode model could be extended to the sequence discrimination task.

According to the Durlach-Braida model, a subject can employ two different processing modes in a discrimination task: a trace mode and a context mode. In the trace mode, the comparison operation is performed on internal memory traces of the input signals. The trace is a direct representation of the acoustic input, e.g. a precategorical replica, and it deteriorates or picks up noise over time. The longer the time interval between two inputs to be discriminated, the more use of the trace mode will lead to degraded performance. In the context mode, each input is first categorized into one of a defined set of codes. The comparison operation is then performed on these encoded representations. Once encoded, the internal data are not subject

to degradation over time. However, there is a context variance present which is a function of the difficulty of the encoding process. Task variables such the stimulus range are assumed to affect this context noise. Performance in a given task will usually involve trade-offs in the internal noise associated with each mode of operation.

These considerations are incorporated into the Durlach and Braida models in the following manner:

$$d' = c_1 / [\sigma_s^2 + (\sigma_c^{-2} + \sigma_t^{-2})^{-1}]^{1/2} \qquad (2)$$

where c_1 is a constant in our tasks incorporating factors such as the detectability and discriminability of the elementary tones (in a minimum uncertainty task), and,

σ_s^2, σ_c^2, and σ_t^2 are variance components added to the discrimination process as a consequence of the sensory, context, and trace aspects of the task, respectively. It can be seen from an examination of equation 2 that the trace and context variances will operate together in determining which process, or whether either process, will have a large effect on perfomance. For example, if the variance associated with one process is much smaller than the variance associated with the other process, the smaller process will have the dominant effect.

The sensory variance refers to the noise from internal and external sources other than those associated with the encoding and storing of the sequence information. In the sequence discrimination paradigm the sensory variance is assumed to be small relative to the context and trace variances. The context variance is assumed to be a function of the number of different sequence patterns that may be present on a trial. The trace variance is assumed to be a function of the time period over which the information from the first sequence, e.g. the trace datum, must be held in order to make a comparison with the information from the second sequence.

Consider the discrimination model applied to the conditions in the sequence comparison tasks of the present study. Suppose that the two sequences of a trial have identical temporal envelopes, as in the correlated condition of figure 1. A direct comparison of the traces of the two sequences will be a good strategy for discriminating any difference in the frequency patterns, provided that the time period between the sequences is not excessive. In the uncorrelated condition, when the two input sequences do not share identical temporal patterns, the use of the trace mode may not be effective. This is because there are now differences between the traces of the two inputs that are not relevant to the frequency discrimination task. These irrelevant differences are associated with the decorrelation of the temporal envelopes of the two sequences. We would expect these

differences to result in added variance in the trace comparison process. This reasoning led us to define the trace variance as follows:

$$\sigma_t^2 = c_2 [ISI + nd + (n-1)g] + c_3 f(\sigma_g^2, g, \ldots) \qquad (3)$$

where c_2 and c_3 are constants, ISI is the inter-sequence-interval, n is the number of tones in each sequence, d is the average duration of each tone, g is the average duration of the gaps between the tones, σ_g is the gap standard deviation, and f( ) is a function describing the added variance due to the decorrelation of the temporal envelopes of the sequences to be discriminated. This function incorporates the effect of irrelevant (i.e. not frequency-contour) differences between the sequences on a trial. The effects of such differences will be minimal when context mode processing is dominant.

2.1 Empirical Tests of the Two-process Model

Predictions of specific versions of the model were evaluated in a series of sequence comparison experiments reported in Sorkin (1987b). The results of these experiments are summarized in figures 2 through 4. Figure 2 shows the average performance of three subjects in the conditions illustrated in figure 1. The independent variable is the standard deviation of the time gap between tones. The smooth curves are model fits to the data of the uncorrelated and correlated condition. Performance in the correlated condition in these experiments is generally independent of gap variability; performance in the uncorrelated conditions drops to an asymtotic value. These results have been obtained in a number of different experiments using different rules to generate the different frequency patterns over trials and different frequency-difference manipulations. Performance in the synchronized condition increases slightly as a function of gap variability.

Figure 3 shows performance as a function of the average gap duration, for a fixed level of gap variability. Performance in the uncorrelated condition increases as a function of duration, while performance in the correlated condition drops to the same value. The smooth curves shown in the figure are model predictions based on parameter fits to data in a separate set of conditions in which the mean gap duration was fixed and the gap variability was varied. Two points about figure 3 should be noted: First, the effect of the relative gap variability, σ_g/g, is mainly on performance in the uncorrelated condition (from figure 2 we know that gap variability does not affect performance in the correlated condition). Second, performance in the correlated condition drops at high gap durations, because of the effect of the total sequence duration on the trace decay time.

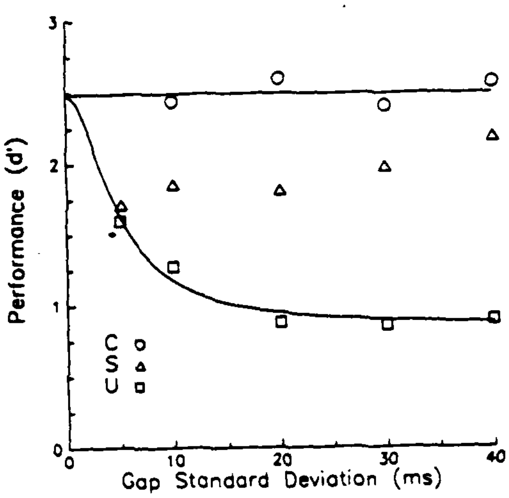

Figure 2. Average performance (plotted points) as a function of the gap standard deviation and condition (C,S,U) (8 tones, mean gap = 100 ms). Solid lines are theoretical functions.

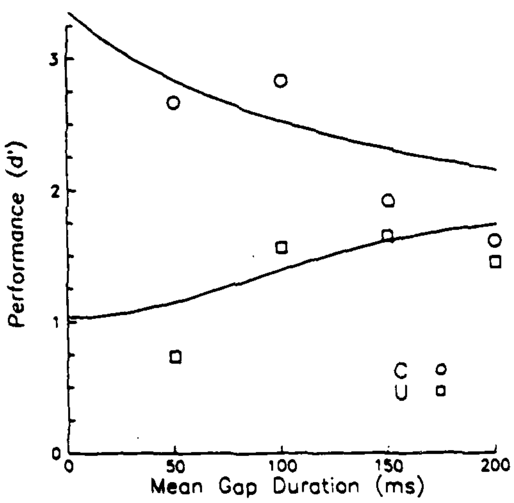

Figure 3. Average performance (plotted points) as a function of the mean gap duration and condition (12 tones, gap standard deviation=40 ms, ISI=0.5 s). Solid lines are theoretical functions based on parameter fits to data obtained with 8 tone sequences at a mean gap of 100 ms and a range of gap variabilities.

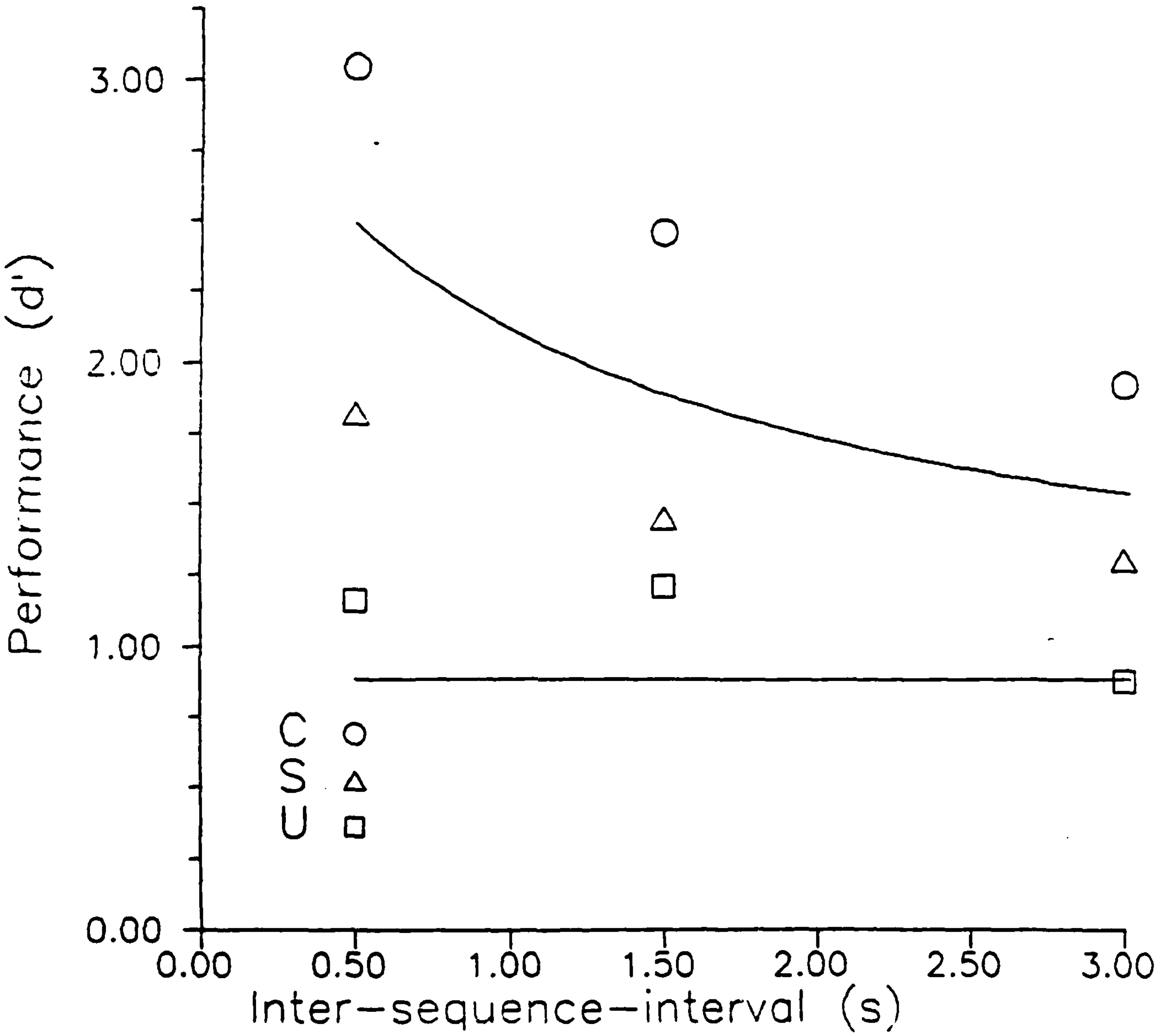

Figure 4. **Average performance (plotted points) as a function of intersequence interval (ISI); same subjects and conditions as figure 2 (8 tones, mean gap=50ms, gap standard deviation=30 ms). Solid lines are theoretical functions based on parameter fits to the data of figure 2.**

The difference between performance in the correlated and uncorrelated conditions is also apparent when examined as a function of the intersequence interval shown in figure 4; performance in the correlated condition drops over intersequence intervals of from 500 to 3000 ms. Performance in the uncorrelated condition is essentially independent of ISI (or drops much more slowly). It is evident that the two-component discrimination model expressed in equations 2 and 3, captures the essential aspects of the results obtained to date. The effects of gap duration and variability, intersequence interval, and correlation, on sequence discrimination performance are all consistent with the model.

The analysis of sequence discrimination behavior into two particular areas: the sensory trace process, and the sequence comparison process. In addition, we have broadened the paradigm to include the discrimination of temporal jitter as a function of the spectral aspects of the patterns. The objective was to better describe the trace process and to assess its sensitivity to certain types of transformations (such as linear time scaling) and to potentially interfering inputs (such as irrelevant sounds occurring during the inter-sequence-interval).

2.2 Experiments on the Trace Mechanism

An important question in sequence comparison is the sensitivity of the trace and context mechanisms to particular types of transformations in the sequences to be compared. The context mechanism is assumed to be insensitive to the length of the ISI and to the effects of certain events occurring during the ISI period. The trace mechanism, on the other hand, is assumed to be highly sensitive to the duration of the ISI and to certain other potentially interfering events, such as the occurrence of similar stimuli during the ISI period. The specific effects of other types of transformations of the sequences are of considerable theoretical interest. Linearly scaling the duration of the initial or final sequence, for example, should have a different effect on performance while in the two modes. Such a scaling may or may not impose additional processing demands on either mode.

2.2.1 Duration Scaling

One interesting question concerns whether duration compression or expansion will produce decrements in the trace mode which are a function of the ISI. That is, will duration scaling interact with the increase in trace variance over time? The answer depends on one's concept of the trace process. If the trace is a true raw representaion of the input, then compressing or expanding the sequence should degrade performance in a fashion similar to the addition of temporal jitter to the sequence intervals, and an interaction will result. If, however, the trace is (effectively) only a partially encoded representation of the tone bursts and the temporal (rhythmic, etc.) relationships among the tone bursts, then such transformations may have a quite different effect. In that case, the effect of such a transformation would not produce interactions with ISI, but

rather would resemble the effects of adding temporal jitter in the context mode: e.g. produce a fixed decrement, depending on the magnitude of the transformation.

We performed some experiments testing these predictions (Sorkin and Snow, 1987). In one experiment, we modified the manner in which the durations of the tones and gaps of the second sequence in a trial were generated. In the 'normal' duration transformation condition, the second sequence in a trial was generated without modification. Trials in this condition were of the same type as those shown earlier. In the 'expanded' duration transformation condition, the durations of all tones and gaps in the second sequence of the trial were multiplied by a factor of 1.4, producing a sequence 40% longer than it would have been without the transformation.

Duration transformation was manipulated factorially with temporal correlation, producing the 'correlated-expanded' condition, in which the two sequences in a trial had the same temporal pattern prior to expansion of the second sequence, and the 'uncorrelated-expanded' condition, in which the temporal patterns of the two sequences in a trial were different prior to expansion of the second sequence. Typical trials from each of these conditions are shown in figure 5.

We were interested in whether operation in the trace mode requires that the two sequences have correlated temporal envelopes. Another way to put the question is to ask whether subjects would treat expansion of the second sequence of a trial as a difference in the sequence temporal patterns- similar to that found in the uncorrelated condition- or if, instead, they would be able to scale the duration of the sensory-trace of one sequence to match that of the other. If such a scaling process were possible, then one would expect to see the same general pattern of results in the correlated-expanded condition as in the correlated-normal condition. If such a scaling process were not possible, then the pattern of performance in the correlated-expanded condition should closely resemble that found in the uncorrelated-normal condition.

The results can be seen in figure 6 and 7. Figure 6 shows performance averaged across subjects for the correlated conditions. Performance in both the normal and expanded cases was independent of gap standard deviation, but decreased with increasing ISI. Figure 7 shows performance in the uncorrelated conditions. In this condition, performance was independent of ISI in the conditions involving large differences in sequence temporal patterns within a trial (i.e. those in which the gap standard deviation was 40), but decreased with ISI in those conditions which did not involve large temporal pattern differnces (i.e. those in which the gap standard deviation was 10). Note that performance in both the uncorrelated-normal and uncorrelated-expanded conditions decreased with increasing gap standard deviation. The results from the 'normal' duration transformation conditions replicate the results of our earlier experiments while the results from the 'expanded' conditions support the proposed duration-scaling hypothesis.

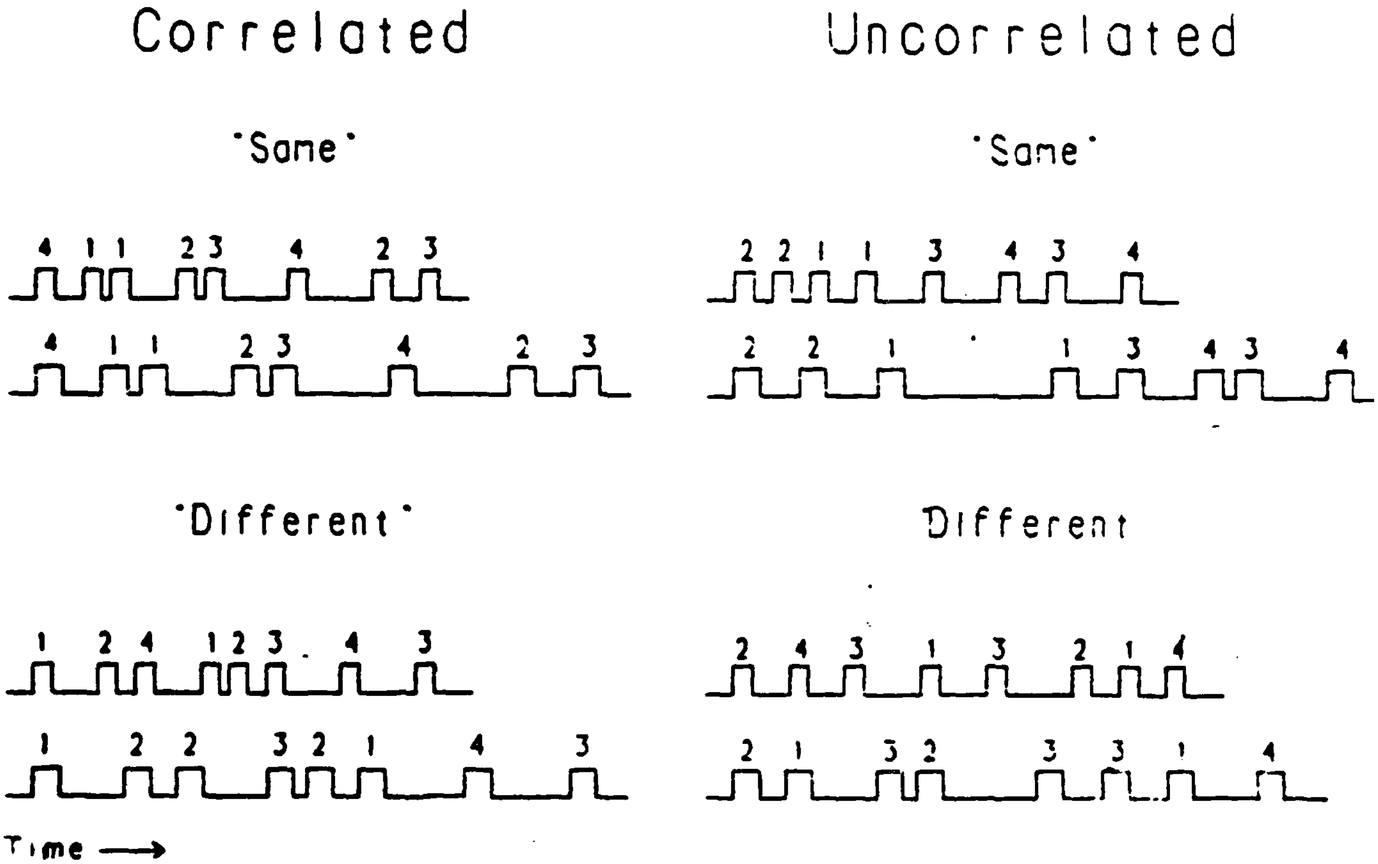

Figure 5. Examples of pairs of tonal sequences in the duration transformation experiment.

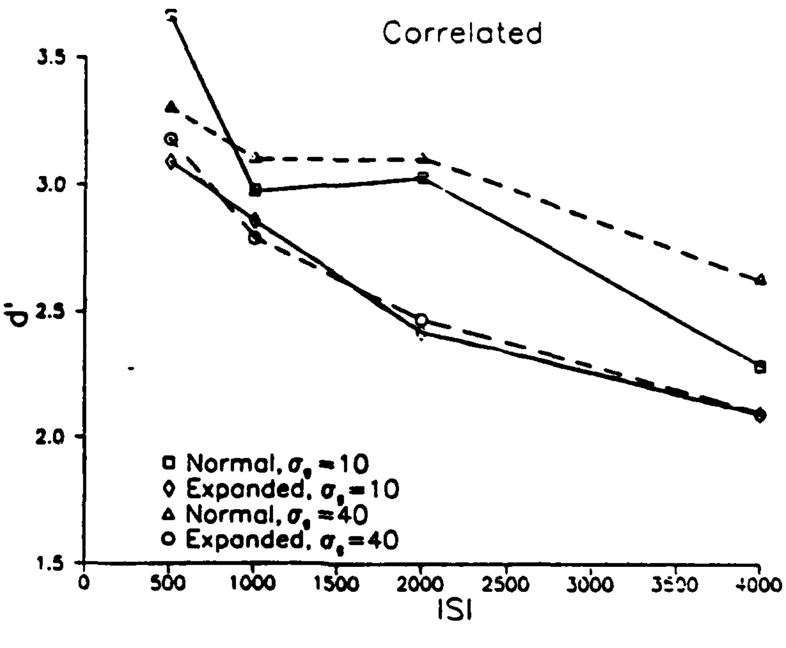

Figure 6. Average performance as a function of inter-sequence-interval, gap standard deviation, and temporal transformation, for the correlated conditions.

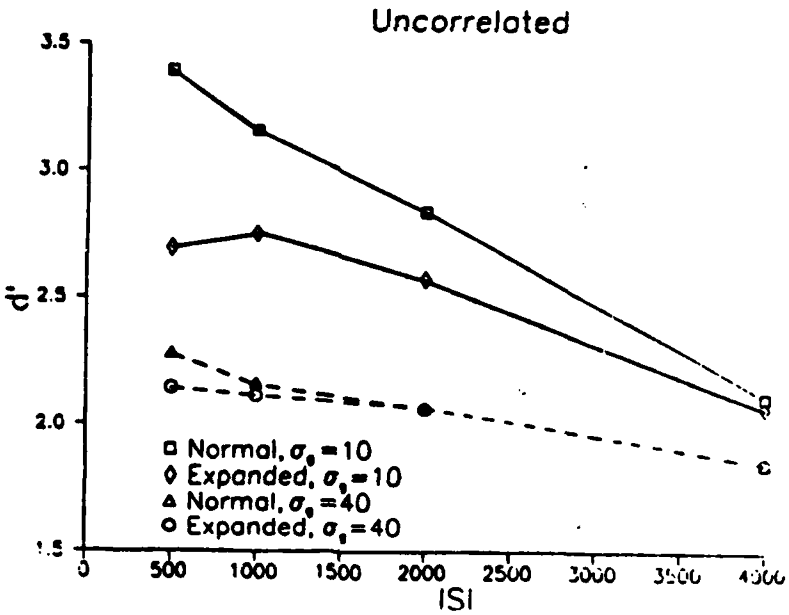

Figure 7. Average performance as a function of inter-sequence-interval, gap standard deviation, and temporal transformation, for the uncorrelated conditions.

Although performance in the expanded conditions is poorer than that in the normal conditions, perhaps due to trace-decay during duration scaling, the general pattern of results is the same, leading one to believe that S's were able to compensate for sequence expansion in these conditions, perhaps by "scaling" the sensory traces.

2.2.2 Frequency Transformation

A second question related to trace transformations concerns the degree to which the trace mechanism is sensitive to frequency transformations. Because of the octave generalization phenomenon, we would expect that the trace would be insensitive to octave frequency transformations, but not to other transformations. An experiment was run in which the observers had to make a same/different judgment on the frequency contour of the sequence. In this task the definition of a correct response is very sensitive to the observer's understanding of the instructions; therefore, one should be cautious in interpretating the results. Four intersequence interval conditions were run (500, 1000, 2000, and 4000 ms.) with four frequency transformations (0%, 10%, 50%, and 100%). Performance dropped from a d' of about 2.5 with 0% transformation to a d' of approximately 1.0 with a 100% transformation; performance dropped about 0.8 d' units between the 500 and 4000 ms. intersequence intervals. There was no significant interaction between frequency transformation and intersequence interval, indicating that observers can not scale frequency in the same way as duration.

2.2.3 Masking

Another experimental manipulation studied in the context of trace vs. context mode processing, was the effect of interfering sound inputs which occur during the intersequence interval. Other investigators, such as Masarro and his colleagues (Kallman and Massaro, 1983) have argued for the occurrence of an interruption in forming and consolidating information from the pre-contextual trace. The correlated-uncorrelated jitter paradigm allows evaluation of the differential effects of such potentially interfering signals. That is, the interfering signal should not only produce effects on performance dependent on the time interval between the offset of the sequence and the onset of the signal, but should also produce effects which demonstrate a shift from trace-mode like processing to context-mode like processing. These effects should be observable as a differential dependence of performance on the gap variability and the ISI.

An experiment to evaluate this hypothesis was performed using 8-tone tonal sequences similar to those described previously (at frequencies of 500, 909, 1667, and 2857 Hz.) equated for perceived loudness (at SPLs of 70, 70, 68, and 64 dBA, respectively). Tone bursts were 50 ms. long with linear onset and offset envelopes of 2 ms. The gap durations were drawn from a normal distribution (approximate) with a mean of 50 ms and a standard deviation of either 10 ms or 40 ms. The intersequence intervals were 1000, 2000, and 4000 ms. The frequency pattern of

the first sequence contained two of each of the four possible frequencies in a random order; if the trial was a 'different' trial, the frequencies of the second or third, fourth or fifth, and sixth or seventh tones in the second sequence (selected randomly) were changed to one of the three remaining frequencies. The correlated and uncorrelated manipulations were the same as described in the previous experiments.

In the masked conditions, a three-tone sequence was played during the ISI, starting 350 ms after the end of the last tone in the first sequence. The duration of each tone in the mask was 50 ms. Mask gap durations were drawn from an approximation to a normal distribution with a mean of 50 ms. In the 'fixed' mask condition, the standard deviation of this distribution was 0 ms. In the 'random' mask condition, the standard deviation of this distribution was 25 ms. Tones in the 'fixed' mask were 1231 Hz, at a level of 70 dBA. Tones in the 'random' mask were selected at random from the set of four which comprised the eight-tone comparison sequences, subject to the constraint that no frequency could occur more than once in the same mask. Trials in the normal phase consisted of a 500 ms visual ready signal, a 500 ms wait, the first sequence, the variable ISI, the second sequence, and observer response followed by trial feedback. Trials in the mask phase were the same except for the occurrence of the mask during the ISI (the total ISI was the same).

Observers had extensive experience in the non-mask conditions, from having participated in previous experiments on sequence discrimination. In the mask phase of the experiment, temporal correlation and mask type were held constant during each sessions (6 blocks of 100 trials), while gap standard deviation and ISI were manipulated factorially across blocks within each test session. The order of ISI and gap deviation was random. There were 8 testing sessions, each observer participating in two blocks from each of the 24 experimental conditions produced by the combination of levels of temporal correlation, mask type, gap deviation, and ISI.

As in our previous experiments, only performance in the uncorrelated conditions decreased with increasing gap standard deviation. Performance in the random mask condition was lower in both the correlated and uncorrelated conditions than performance in the normal or fixed-mask conditions. However, performance in the masked-correlated conditions was superior to that in any of the uncorrelated conditions. Figure 8 shows the averaged results as a function of ISI for the $\sigma = 40$ ms condition. (The pattern of performance obtained in the correlated and uncorrelated conditions for $\sigma = 10$ ms was essentially the same as that found for $\sigma = 40$ ms.) The standard error of each point was estimated by taking the square root of the mean of the variances (Gourevitch and Galanter, 1967) of the individual subject d's. The effects of the masker appear to be independent of the correlated/uncorrelated manipulation. One possible conclusion is that the 'trace' process is not more susceptible to the effects of an intervening masker than is the context process.

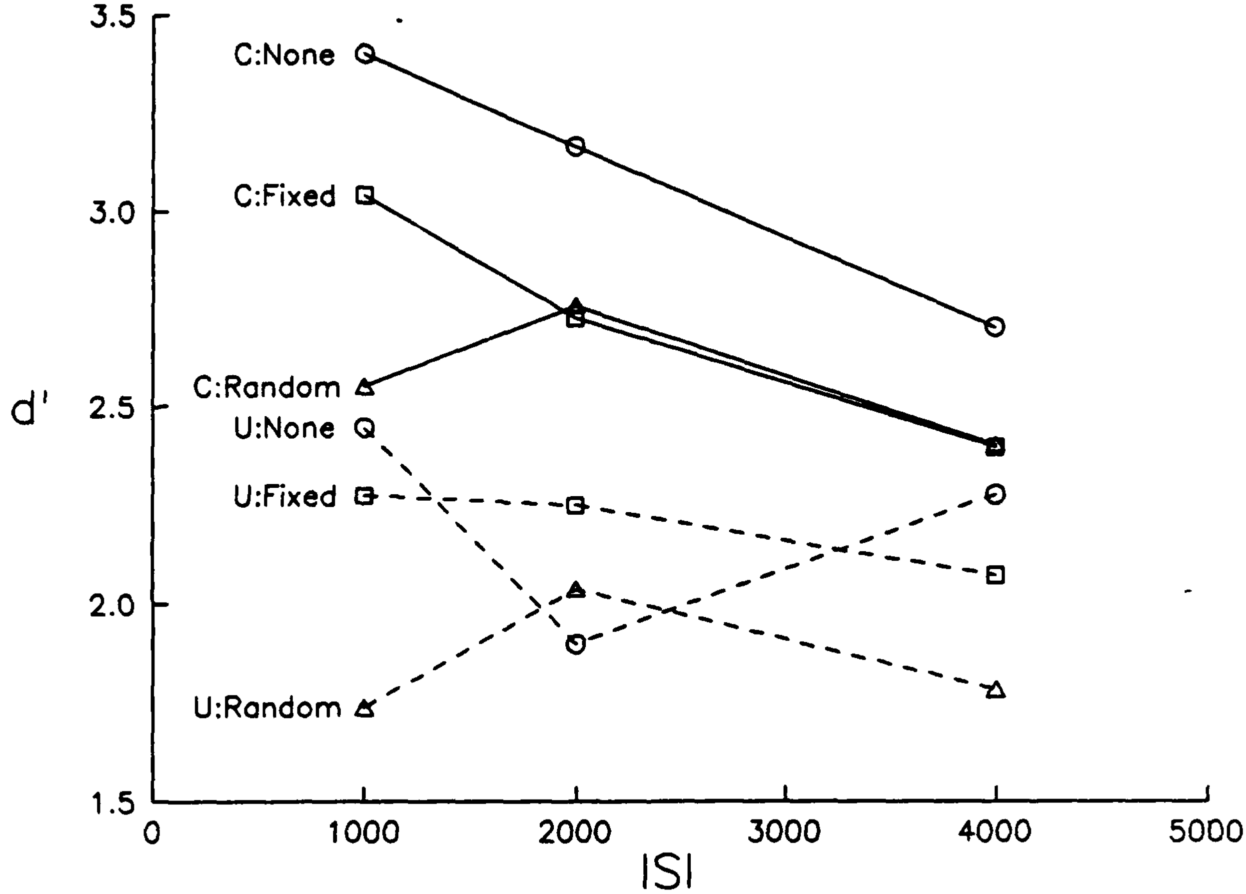

Figure 8. Average performance as a function of intersequence interval with and without intervening masker (gap standard deviation=40 ms).

2.3 Temporal Pattern Discrimination

In these experiments, the observer was asked to disciminate between two tonal sequences which had the same or different temporal or rhythmic, rather than frequency patterns. The initial objectives were to model the discrimination process using the types of sequence comparison algorithms developed for frequency pattern discrimination (e.g. Sorkin, 1987a). In addition, we were interested in testing for the trace/context distinctions observed in the frequency discrimination task and, in addition, in evaluating the effects of temporal transformation or scaling on rhythmic discrimination. The expectation was that discrimination performance would be highly resistant to the temporal scaling manipulation, over a range of time transformations.

The stimuli and conditions were similar to those previously described. Tone sequences consisted of 8, 1000 Hz tone bursts of 50 ms duration at 75 dBA. The intersequence interval was 1000 or 3000 ms. The gaps were approximately Normal with a mean of 50 ms and a minimum gap of 5 ms. On 'same' trials, the durations of the gaps in the second sequence were identical to those of the first. On 'different' trials, jitter was added to the duration of each gap in the first sequence to obtain the durations of gaps in the second sequence. The amount of jitter was determined by a uniform distribution with a mean of 0 ms and a variable standard deviation, σ_{diff}. During the first phase of the experiment, a psychometric function of σ_{diff} was obtained, shown in figure 9. The value of σ_{diff} was varied from 11 to 40 ms (varied across blocks of trials and sessions). Performance increased with σ_{diff} in the expected fashion.

ISI and temporal transformation were varied during the next phase of the experiment; temporal scaling was accomplished by multiplying each tone and gap duration in the second sequence by a duration transformation parameter following normal sequence generation. The jitter was added to sequences in 'different' trials prior to the duration transformation. There were seven duration transformation conditions (varied across blocks) ranging from 0.4 (maximum compression) to 1.6 (maximum expansion). Observers were informed prior to each session, which transformation condition they were running. σ_{diff} was held constant at 30 ms; the order of presentation of the duration transformation condition was random (but with no repeats). An additional set of conditions were run in which the first sequence in each trial were also duration-transformed; in other words, additional control conditions were run in which the average onset to onset intervals were held constant within a trial and block. These effectively non-transformed conditions enable us to factor out the effect of duration on the duration transformation task.

The results of the temporal transformation manipulation are shown in figures 10 and 11. The top curve of figure 10 indicates how temporal discrimination improves with net total average duration of the sequence, for a fixed ratio of σ_{diff} to tone+gap duration. The lower curve shows the effect of transformation in the condition when the second sequence is transformed relative to

the first. Figure 11 shows the effect of transforming the second sequence when the effect of duration is factored out. It can be seen that the effect of temporal transformation is relatively symmetric about zero and that the resulting function is highly peaked. Little effect of ISI can be observed on performance. This sensitivity to expansion or contraction was unexpected and is not consistent with our current models of the discrimination process (especially in light of the lack of an effect of ISI). Because of the presence of across-trial variation in the gaps, and because of the manner in which the difference jitter was added, this discrimination task is relatively complicated to define from an ideal observer's point of view. Accordingly, we have modified the task somewhat in our current experiments.

3. DETECTION AND RECOGNITION OF MULTIPLE ELEMENT SIGNALS

In addition to these experiments on sequential auditory inputs, we have continued to gather data on detection with multi-element auditory and visual signals. These experiments are designed to evaluate how information relevant to a detection decision is aggregated over multiple display elements (either in a sequence of display elements, or in a simultaneous presentation of display elements). We reported some of these results in Sorkin et al. (1987) in Sorkin, Mabry, and Weldon (1988), and in Mabry (1987). Experiments have continued on two questions: (a) the effects of varying the statistics of the displayed elements over the spatial position of the display, and (b) whether the recognition-detection model (Green and Birdsall, 1978; Green, Weber, and Duncan, 1977) is valid for the multiple-element situation. The data acquisition phase of this project was completed; initial analysis indicates support for the extension of the recognition-detection model.

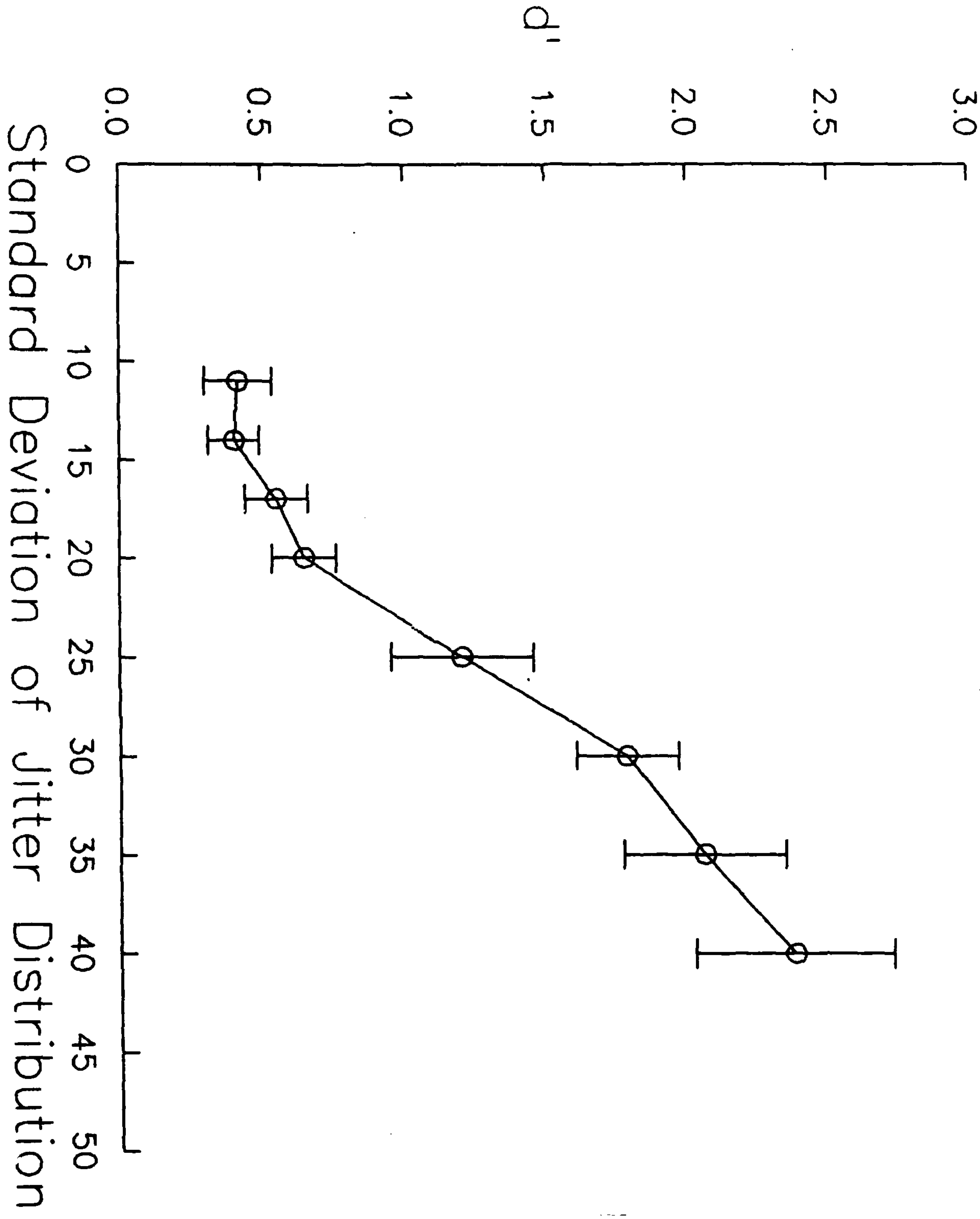

Figure 9. **Average performance in the temporal discrimination task as a function of the standard deviation of the difference jitter.**

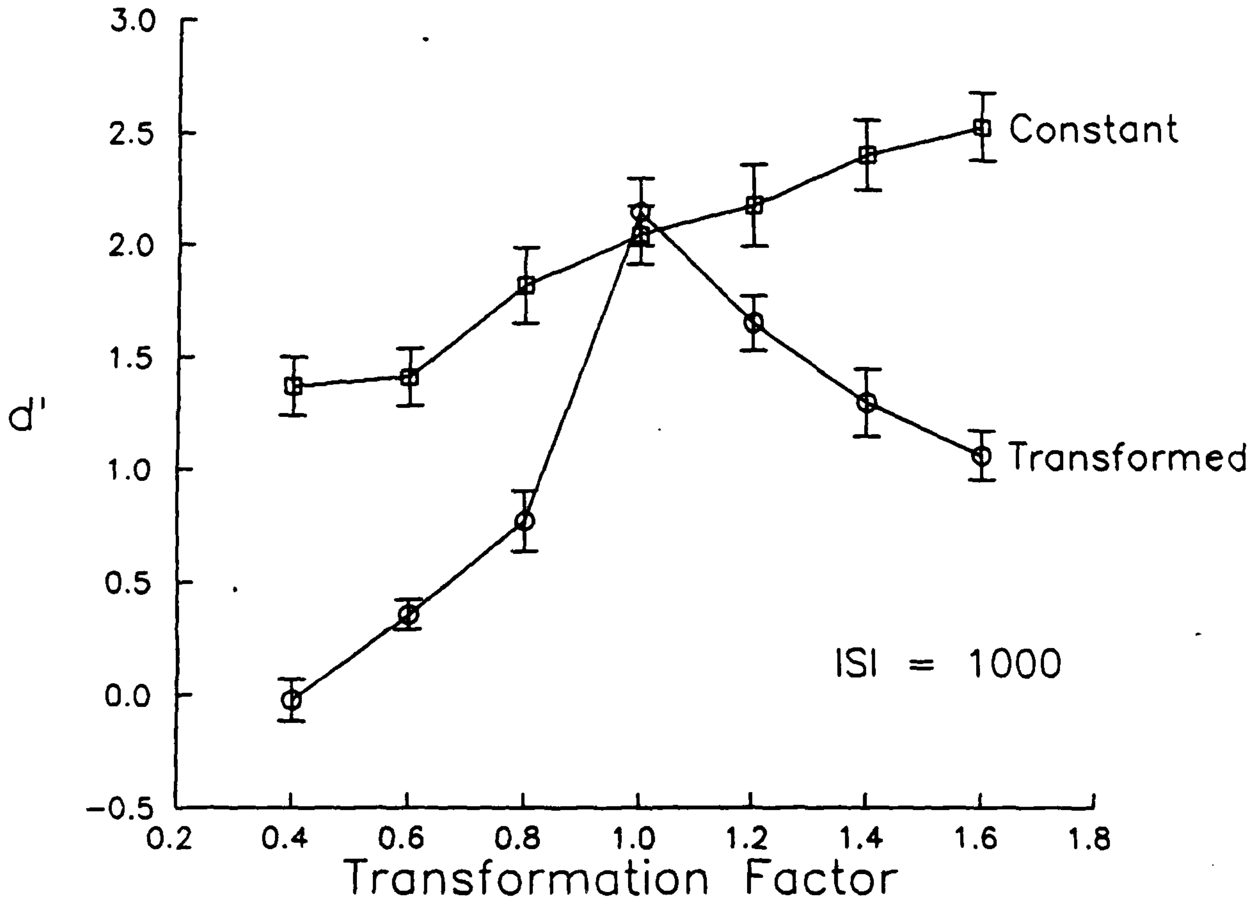

Figure 10. Average performance in the temporal discrimination task as a function of the transformation factor. The top curve is the condition when both sequences undergo the same transformation; the abscissca is proportional to average duration. The lower curve is the condition when only the second sequence is transformed.

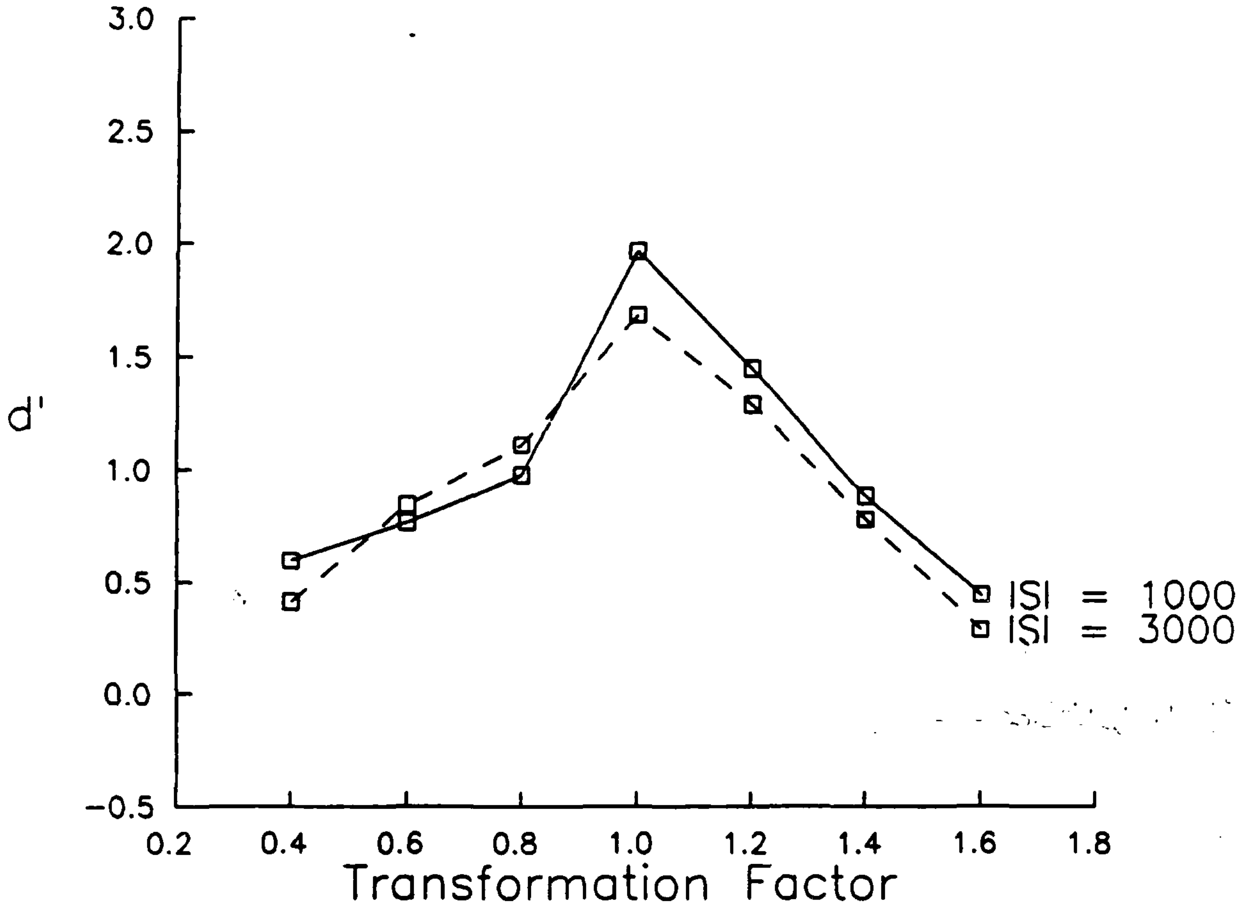

Figure 11. **Average performance in the temporal discrimination task as a function of the transformation factor. The data in the lower curve of figure 10 have been corrected for the effect of duration.**

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5. PROJECT PERSONNEL

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6. ADVANCED DEGREES/DISSERTATIONS

Master of Science to T. R. Mabry. *A Detection Theory Analysis of Visual Displays*, Purdue University, December, 1987.

Doctor of Philosophy to G. C. Elvers. (expected), Purdue University, May, 1989.

7. PUBLICATIONS and MANUSCRIPTS

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8. INTERACTIONS

Meeting of the Acoustical Society of America, Miami, Fl., November 1987. Sorkin, R.D. and Snow, M.P. Discrimination of time-expanded tonal sequences. J. Acoust. Soc. Amer., 1987, 82, S40.

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Member, National Research Council/Committee on Hearing, Bioacoustics and Biomechanics.

Panelist, National Research Council/Committee on Hearing, Bioacoustics and Biomechanics, Panels on the classification of Complex, Non-speech Signals, and the Removal of Noise from a Speech/Noise Signal.